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Bathymetric Survey of Imja Lake, Nepal in 2012

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ABSTRACT

Imja Lake is one of the most studied lakes in the Himalaya as well as one of the most rapidly evolving glacial lakes in Nepal. Many researchers have studied the lake and the potential of a glacier lake outburst flood from the lake. One of the important factors in assessing the outburst flood risk is the volume that could be released in the flood and good bathymetric data is necessary to estimate that value. This work reports on the 2012 bathymetric survey of Imja Lake and the rate of expansion that has been observed in the lake over the last two decades, since 1992. The survey was somewhat hampered by the extensive iceberg coverage of the lake in September 2012, but a good estimate of the bottom bathymetry and the current volume was obtained. When compared to previous surveys, it is very clear that the lake bottom has continued to deepen as the ice beneath the lake has melted. The average depth has increased by 62% since 2002 and continues to increase at a rate of 1.8 m/yr. The maximum depth has increased 28% since 2002 and is increasing currently at a rate of 5.8 m/yr. Perhaps more important in terms of glacier lake outburst flood risk is the continued rapid areal expansion of the lake which has expanded 41% since 2002 and is growing at a rate of 0.02 km²/yr. This expansion has resulted in an additional 6 million m³ of water for an outburst flood event, and increasing the maximum possible flood volume to 36.3 million m³ a 73% increase from what was calculated using 2002 data.

KEYWORDS: Imja Lake, Bathymetry, Nepal, Glacier Lake Outburst Flood, Climate Change

1 INTRODUCTION

1.1 Glaciers and climate change, Glacier lakes and GLOFs in Nepal

Newly forming glacier lakes in high mountain regions of the world present a risk of Glacial Lake Outburst Floods (GLOFs), a significant hazard related to glacier recession and temperature increase due to climate change (Kattelmann 2003; and Richardson & Reynolds 2000). A GLOF is a sudden release of a huge amount of water from a glacier lake into the downstream river, many orders of magnitude higher than the normal flow, due to a triggering mechanism (often a breach of an unstable moraine dam) (Carrivick & Rushmer 2006). GLOFs can affect fragile mountain ecosystems as well as economic activities due to the large magnitude and power of the flood flow comprised of water and debris (Bajracharya et al. 2007).

The formation of glacier lakes in the Nepal Himalaya has been increasing since the early 1960s. According to Bajracharya et al. (2007), 24 new glacial lakes have formed and 34 major lakes have grown substantially during the past several decades in the Mt. Everest and Makalu-Barun National Parks of Nepal. Accompanying this increase in the number and size of glacier lakes is an associated number of GLOF events (Ives et al. 2010; Shrestha & Aryal 2011) which now occur on average every 3 to 4 years in the eastern Himalaya (Yamada & Sharma 1993; Kattelmann 2003). The appearance and danger posed by glacier lakes in this region has prompted national and regional groups to assess the increasing GLOF risk to communities downstream of the lakes. Fourteen GLOF events that have originated within Nepal during the past several centuries and only one of these events occurred prior to 1960 (Yamada & Sharma 1993; Ives et al. 2010). An additional 10 events have originated outside Nepal and caused significant damage within the country.

The Khumbu region of Nepal (Figure 1) is regularly mentioned as an area particularly prone to GLOF events and containing important sites for possible GLOF risk reduction projects. Bajracharya et al. (2007) suggest that at least twelve (12) of the new or growing lakes within the Dudh Koshi watershed of the Khumbu region of Sagarmatha National Park may be dangerous from the standpoint of future GLOFs. Several of these lakes are classified as “potentially dangerous” based on their rapid growth over the past several decades as evidenced through the use of time lapse, remotely sensed imagery (Bajracharya et al. 2007; Jianchu et al. 2007; Bolch et al. 2008; Watanabe et al. 2009). Imja Lake is located in the Imja Khola a sub-basin of the Dudh Koshi and it is often mentioned as one of the most dangerous glacial lakes in the Khumbu region (Hammond 1988; Kattleman 2003; Ives et al. 2010; ICIMOD 2011). Much of this attention stems from the fact that it is in a famous region on the Everest Basecamp trekking route and there would be significant economic costs for the region if a GLOF were to occur (Hammond 1988; Watanabe et al. 1994; ICIMOD 2011). Two previous GLOFs have occurred in the Khumbu region in recent years: in 1977 from Nare Tsho and in 1985 from Dig Tsho glacier lakes. Nare Lake, a tributary of the Imja Khola situated on the southern slope of Ama Dablam in the Mingbo Valley, was formed by a moraine dam having an ice-core. A GLOF event occurred on September 3, 1977 when a small glacial lake located at a higher elevation discharged into Nare Lake causing the lake to overtop its damming moraine and creating a GLOF into the Imja Khola and finally the Dudh Koshi below. Several lives were lost in the resulting flood and bridges were destroyed for 35 km downstream (Buchroithner et al. 1982; Fushimi et al. 1985; Zimmerman et al. 1986; Hammond 1988; Mool et al. 2001; Ives et al. 2010). Dig Tsho glacial lake contacts the Langmoche glacier and drains into the Bhoti Koshi tributary of the Dudh Koshi. On August 4, 1985 an ice avalanche fell into the lake, which had little freeboard at that time, resulting in a wave that overtopped the moraine dam and caused a breach in the moraine. The resulting GLOF destroyed the Namche Hydropower Plant (11 km downstream), 14 bridges, trails, cultivated land, and caused the loss of several lives (Hammond 1988; Ives 1986; Vuichard & Zimmerman 1986, 1987; Mool et al. 2001; Ives et al. 2010).

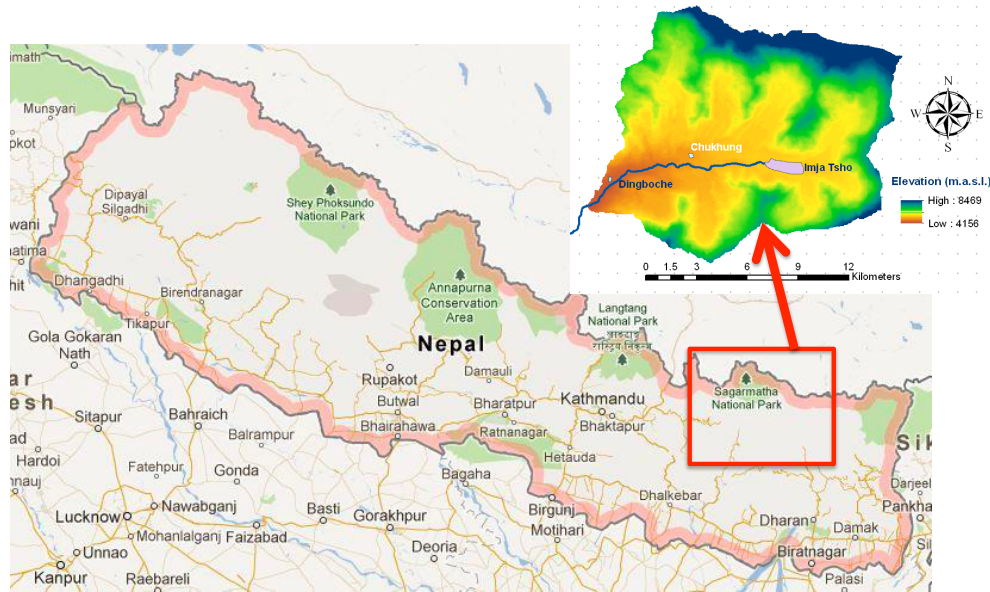


Figure 1. Location of Imja Khola basin within Nepal. (Source: Google Earth and the authors)

Hammond (1988) identified twenty-four glacier lakes and numerous other melt water ponds in the Khumbu region in 1988. Most of these lakes began forming in the late 1950s to early 1960s and have expanded considerably ever since, especially the supraglacial Imja Lake (see Figure 2). The original 1963 Schneider map of the Everest region does not show a supraglacial lake on the Imja Glacier, but it does show five large ponds on the surface of the glacier (Hagen et al. 1963). The lake has experienced rapid growth in area and volume since in the early 1960's, leading to concern about the risk of a catastrophic GLOF event. Watanabe et al. (2009) provide a full account of the growth and development of Imja Lake. Bolch et al. (2011) studied the mass change for ten glaciers in the Khumbu region south and west of Mt. Everest. The Imja glacier area (including the Lhotse Shar glacier) was found to be 10.7 km^2 (in 2007) with a specific mass balance of $-0.5 \pm 0.09 \text{ m/yr}$, the largest loss rate in the Khumbu region. The high mass loss rate of the Imja glacier results from a complex mixture of processes including calving losses at the glacier terminus along with large areas of the glacier surface with comparatively thin debris cover.



Figure 2. Location of Imja Lake (Source: Google Earth, 2010)

The risk of a GLOF from Imja Lake has been investigated for more than 20 years (Armstrong, 2010). In particular, the development of the lake has been reported in Hammond (1988), Yamada & Sharma (1993), Watanabe et al. (1994), Watanabe et al. (1995), Yamada (1998), and Bajracharya et al. (2007). Imja Lake has been reported by Fujita et al. (2009), Watanabe et al. (2009), and ICIMOD (2011) to be relatively stable, that is, at that time it was not considered to be in danger of producing a GLOF but should be monitored regularly. A GLOF from Imja Lake could affect villages that are nearby downstream, e.g., Dingboche, 8 km downstream of the lake's terminal moraine. Figure 2 shows the geographic locations of Imja Lake and Dingboche. The population in the downstream village areas is about 96,767 for Imja, and about 5,784 to 7,762 people would likely be affected by a potential GLOF, with up to 501,773 people indirectly affected through infrastructural damage and loss of goods and services (ICIMOD, 2011). Imja Lake lies within one of the top 10 tourist destinations in Nepal, with more than 32,000 tourists visiting the region annually (Sagarmatha National Park, 2011). Hammond (1988) and Watanabe et al. (1995) note the large number of trekkers at risk from an Imja Lake GLOF. Destruction from an Imja GLOF could be expected to destroy 40% of the trail from Lukla to Nanche Bazar, 3 bridges from Namche to Pheriche, and the trail from Dingboche to Imja lake would be mostly destroyed as well (Hammond 1988; Watanabe et al. 1995). The economic costs of this destruction, combined with the economic loss from declined tourism, certainly would be very damaging to the local and perhaps national economy.

Hammond (1988) presented one of the first descriptions of Imja Lake and the potential consequences of a GLOF from the lake. She noted that glacial lake hazards are not widely recognized and are somewhat obscure to government administrators as well as villagers and trekkers who pass near to these remote sites and that there is very little information about the processes that result in these events or the effects of them. Little has changed from the time that description was written, over 25 years ago. GLOFs have rarely been observed and the lakes that cause them are located in remote locations and few data are collected to monitor them or calibrate models to predict the effects of other events. Imja Lake has been studied by a number of researchers, but many of the more remote lakes in the region pose as great or greater risks and go unstudied and almost nothing is known about them (Byers et al. 2012). Many have suggested using remote sensing technology as a means of monitoring glacial lakes (Hammond 1988; ICIMOD 2011); however, recent work of the authors has shown that the likelihood of mistakenly characterizing a lake as either dangerous or not is extremely high, especially in the Nepal Himalaya (Byers et al. 2012).

In September 2011, May 2012 and September 2012, the authors visited Imja Lake and observed the rapid rate of change of the terminal moraine complex and the glacier terminus. They also performed ground penetrating radar (GPR) surveys of most of the terminal moraine complex and mapped the ice core of the moraine (Somos et al. 2012). The authors also performed a sonar bathymetric survey of Imja Lake and the outlet. This paper reports the results of the bathymetric survey performed in 2012 and complements the previous bathymetric surveys done in 1992 (Yamada & Sharma 1993) and in 2002 (Sakai et al., 2003) to estimate the volume expansion rate of Imja Lake.

1.2 Imja Glacier and Lake

Imja Lake is located in the Khumbu region of the Nepal Himalaya (27.898 N, 86.928 E), about 9 km south of Mt. Everest. The lake is bounded on the east by the Imja Glacier, on the north and south by lateral moraines, and to the west by a terminal moraine (Figure 3). Imja Lake is dammed by an 700 m wide by 600 m long ice-cored terminal moraine complex through which water exits the lake by means of an outlet lake complex (Watanabe et al. 1994; Watanabe et al. 1995; Somos et al. 2012). The incision of the outlet channel complex has lowered the lake level by some 37 m over the last four decades (Hambrey et al., 2008; Watanabe et al., 2009; Lamsal et al, 2011). The terminal moraine clearly still contains ice evidenced by outcrops of bare ice, ponds formed by melt water from ice in the moraine (Figure 4), and traces of old ponds (Somos et al. 2012; Yamada & Sharma 1993). It is likely that the outlet lake complex is evolving into a new arm of the lake (Benn et al 2012). The outlet flow from the lake forms the Imja Khola (river), which is a tributary of the Dudh Khosi. The area of the Imja basin is about 141 km² with altitude ranging from 4355 to 8501 m and it is about 38% covered by glaciers (Konz et al., 2005).



Figure 3. Imja Lake, September 2012 (*Photo: Daene McKinney*)



Figure 4. Imja Lake with blue ice melt water ponds in foreground (*Photo: Daene McKinney*)

The Imja glacier has been extensively studied (e.g., Hammond 1988; Watanabe 1994, 1995, 2009; Yamada & Sharma 1993; Yamada 1998; Chikita et al. 2000; Sakai et al. 2003, 2005, 2007; Gspurning et al. 2004; Quincey et al. 2005, 2007; Byers 2007; Sakai et al. 2007; Bajracharya et al. 2007; Bolch et al. 2008; Hambrey et al. 2008; Fujita et al. 2009; Ives et al. 2010; Lamsal et al. 2011; Benn et al. 2012). Several authors have discussed the development of Imja Lake (Quincey et al. 2007; Bajracharya et al. 2007; Byers 2007; Yamada 1998; Watanabe et al. 2009; Ives et al. 2010; and Lamsal et al. 2011). Lamsal et al. (2011) give a general description of the evolution of the Imja glacier and lake since the early 1960s. Imja Lake appeared during the 1960s after several small ponds on the glacier coalesced into an emerging glacier lake. Measurements in 2002 showed the average depth of the lake had grown to 41.6 m with a maximum depth of 90.5 m and a volume of 35.8 million m³ (Sakai et al. 2003). By 2007 the lake was about 2000 m long, 650 m wide, and an area of about 1.03 km² (Watanabe et al. 2009). Table 1 and Figure 5 show the areal expansion of the lake from the early 1960s until September 2012. Although the lake has expanded rapidly in the last 50 years, most of the expansion has occurred through calving of the eastern end of the glacier and not through narrowing of the terminal moraine (Hambrey et al., 2008). The down-valley expansion in the direction of the terminal moraine has stabilized in recent years while the up-glacier expansion continues unabated (Watanabe et al., 2009). However, the authors observed extensive expansion toward the face of the terminal moraine during 2011-2012.

The lateral moraine troughs act as gutters, trapping debris derived from rockfall, snow avalanches and fluvial transport (Hambrey et al., 2008). The Imja Glacier still covers the area

beneath Imja Lake and melting of this ice has caused the lake level to fall in recent decades (Watanabe et al. 1995; Fujita et al. 2009). Although, knowledge of the vertical lowering of the Imja glacier and lake as well as the terminal moraine complex is minimal, Lamsal et al. (2011) report the average lowering of the glacier surface for the period 1964 to 2006 in the area west of the lakeshore was 16.9 m. The average lowering in the up-glacier area east of the lakeshore during this period was 47.4 m.

Table 1. Imja Lake Area Expansion 1962 to 2012.

Year	Area (km ²)	Source
1962	0.03	Bajracharya. et al. (2007)
1975	0.30	Bajracharya. et al. (2007)
1983	0.56	Bajracharya. et al. (2007)
1989	0.63	Bajracharya. et al. (2007)
1992	0.64	Yamada & Sharma (1993)
2000	0.77	Bajracharya. et al. (2007)
2001	0.83	Bajracharya. et al. (2007)
2002	0.86	Sakai et al. (2003)
2006	0.91	Lamsal et al. (2011)
2007	1.03	Watanabe et al. (2009)
2009	1.01	Watanabe et al. (2009)
2010	1.05	This study
2012	1.21	This study

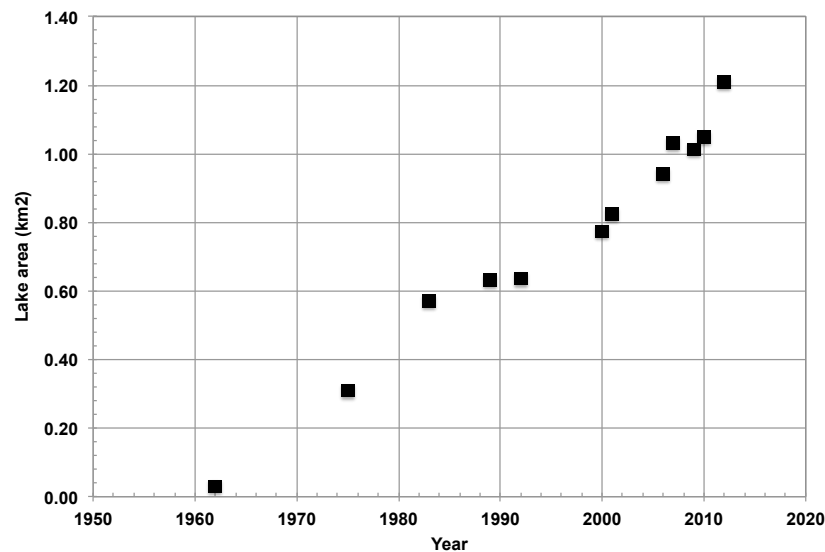


Figure 5. Imja Lake Expansion 1962-2012.

2 SURVEY

2.1 Equipment

A bathymetric survey of Imja Lake was performed September 22 and 24, 2012 using a sonar bathymetric surveying unit mounted on an inflatable boat. The equipment and the survey are described in this section. The results of the survey and comparison to previous bathymetric surveys conducted in 1992 (Yamada & Sharma 1993), 2002 (Sakai et al. 2003) and 2009 (ICIMOD 2011) are described in the next section.

A Biosonic EchoSounder MX system was used to conduct the bathymetric survey. The system consists of three components: (1) a surface unit; (2) a transducer; and (3) a computer. The surface unit operates on 12v DC power and is contained in a protective case that houses the sonar transmitter and provides power and data connection to the transducer. The surface unit generates and receives information from the transducer, processes the signal into a usable format, combines GPS data from an internal Garmin GPS 15xH unit and transmits the raw data to the computer. The transmitter generates the sonar pulse and sends the signal to the transducer. The transducer converts the signal from the transmitter into an acoustic pulse and transmits that energy into the water. The transducer also receives acoustic echos and converts them to electrical signals and transmits them to the surface unit through the transducer cable. A Panasonic Toughbook laptop computer is used to run the visual acquisition software to process the data received from the transducer and surface unit. The transducer is mounted on a pole connected to the rear of the boat. The system produces a ping rate of 5Hz, and an accuracy of 1.7cm +/- 0.2% of depth, with a depth range of 0-100m. The transducer has a single frequency – 204.8 kHz with a beam angle of 8.5 degree. Figure 6 shows the EchoSounder sonar equipment in the boat at Imja Lake.

One of the unexpected situations encountered during the survey was the massive wastage of the Imja Glacier into the up-glacier end of the lake due to calving of the glacier between May and September 2012 (see Figure 7). This made the approach to the ice cliff at the east end of the lake impossible and very dangerous, so this was not attempted. Figure 8 shows the Imja Glacier end of the lake during September 2011 (top) with most of the glacier cliff intact and again in September 2012 (bottom) with a considerable amount of the cliff calved off into the lake. The retreat of the glacier was very rapid during this period and this is still being analyzed since it was a significantly greater recession than has been observed in previous years and may represent an accelerating process of glacier recession. Another unexpected event was that the lake was not expected to be deeper than 100 m.

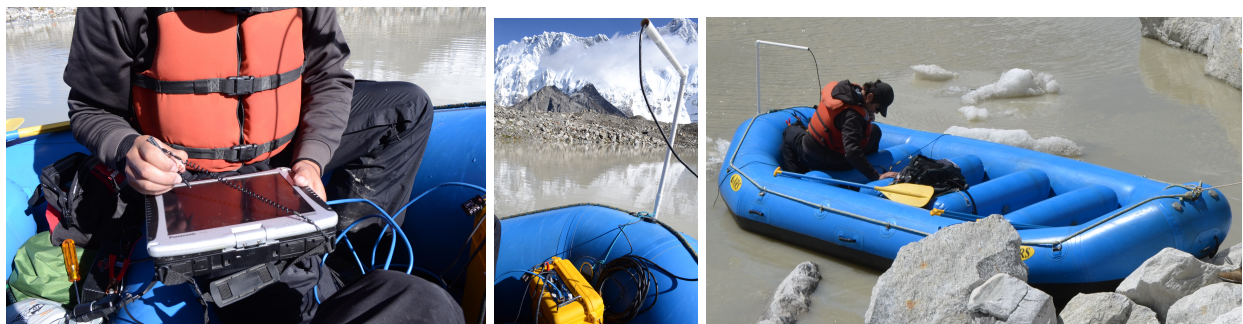


Figure 6. The EchoSounder sonar equipment in the inflatable boat at Imja Lake (*Photos: Daene McKinney*)



Figure 7. Icebergs present in Imja Lake during Bathymetric survey. (*Photo: Mark Woods*)



Figure 8. Glacier end of Imja Lake September 2011 (top) and 2012 (bottom). (*Photos: Daene McKinney*)

2.2 Survey

Several transects with the sonar system in the inflatable boat were made across the lake and the lake outlet complex on the terminal moraine of the lake (Figure 9). Floating ice that had calved off from the glacier was a constant concern during the survey, since a collision with an iceberg could damage the sonar equipment or sink the boat (Figure 10). Getting too close to the shore was also a major hazard since the sonar sensor could hit the shallow bottom there and become damaged and there are regular rock avalanches into the lake from the very tall and unstable lateral moraines of the former glacier. At the beginning of the survey each morning about 2 cm of ice covered the lake surface, making rowing difficult.

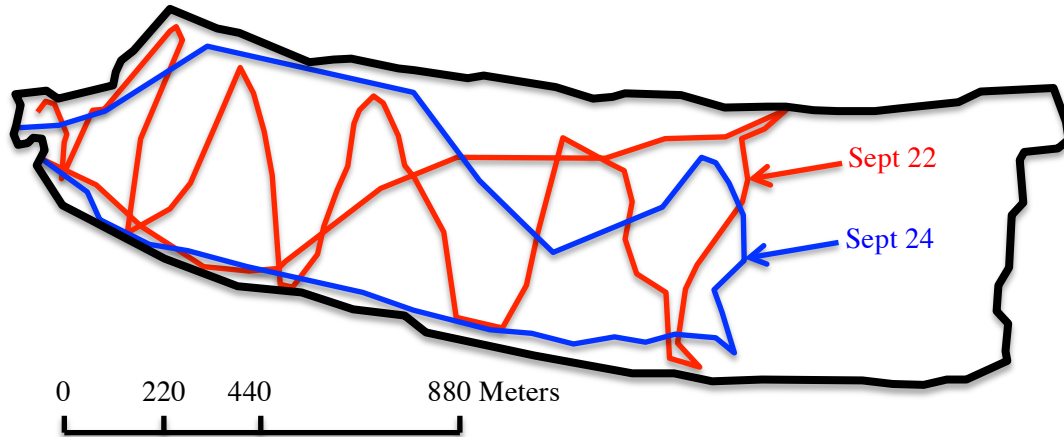


Figure 9. Transects performed during Imja Lake bathymetric survey on September 22, 2012 (Red) and September 24, 2012 (Blue).



Figure 10. Paddling the boat in Imja Lake (left). Avoiding icebergs in Imja Lake (right) (Photos: Daene McKinney)

3 RESULTS

Figure 11 shows a contour map of the depth of the bottom of Imja Lake derived by interpolating the sonar measurements. During the transects back and forth across the lake, water depths of 20-60 m were measured near the western edge of the lake (outlet end) and 30-100+ m deep near the eastern (glacier) end of the lake. Due to the thick iceberg coverage on the eastern edge of the lake, transects at the far eastern end of the lake were not possible. Elevations deeper than 100 m within the 100m-contour have been interpolated from the surrounding values and the slope at the up-glacier end (eastern) of the lake has also been approximated. It is very clear, when compared to the previous surveys (Yamada & Sharma 1993; Sakai et al. 2003; ICIMOD 2011) that the lake bottom has continued to deepen as the ice beneath the lake has melted (this will be discussed in more detail below).

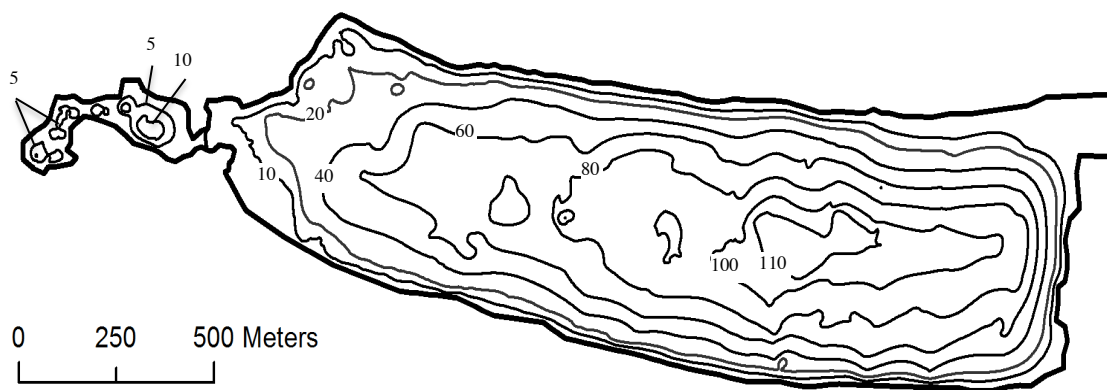


Figure 11. Bathymetric survey results from Imja Lake.

The results of the bathymetric survey are shown in Table 2, which also shows the results of the previous bathymetric surveys performed at Imja Lake (Yamada & Sharma 1993; Sakai et al. 2003; ICIMOD 2011). The 1992 measurements were taken at 61 points around the lake through holes drilled in the ice and using a 100 m long fishing line and weight (Yamada & Sharma 1993). The 2002 bathymetric data were taken at 80 uniformly spaced points on the lake using a weighted fishing line (Fujita et al. 2009). The 2009 survey was to have been conducted using a sonar device, but it malfunctioned and the survey had to be completed by hand similar to the 1992 and 2002 surveys (ICIMOD 2011).

The previous maximum depth measured in bathymetric surveys was 98 m (Yamada & Sharma, 1993). The maximum depth measured by the sonar sensor in this bathymetric survey was 100 m, but a maximum depth was approximated from the sonar data by interpolation as 116 m. The data presented here significantly change the estimate of the volume of water in the lake from 35.5 million m^3 estimated in 2009 (ICIMOD 2011) to 63.8 million m^3 from this survey, almost double the previous estimate. The 2009 estimate (ICIMOD 2011) of the lake volume is less than that estimated in 2002 (Sakai et al. 2003), possibly because it had to be completed by hand (ICIMOD 2011). In any case, the 2002 volume estimate was 35.8 million m^3 . Figure 12 shows the outline of Imja Lake in February 2010 when the area was 1.056 km^2 , and again in June 2012 when area was 1.214 km^2 .

Table 2. Imja Lake Bathymetric Survey - Results

Study	Area (km^2)	Volume (10^6 m^3)	Average Depth (m)	Maximum Depth (m)
1992 ¹	0.60	28.0	47.0	98.5
2002 ²	0.86	35.8	41.6	90.5
2009 ³	1.01	35.5	35.1	96.5
2012 ⁴	1.21	63.8	52.6	116

¹ Yamada & Sharma (1993)

² Sakai et al. (2003)

³ ICIMOD (2011)

⁴ This study

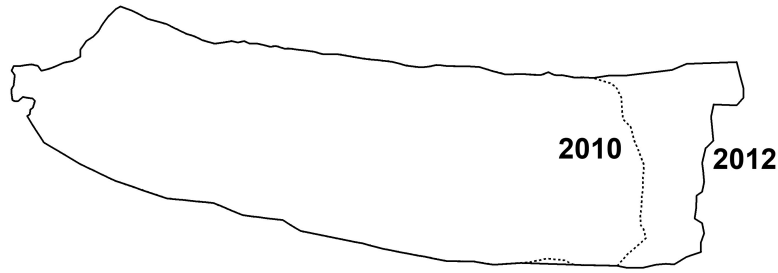


Figure 12. Outline of Imja Lake in February 2010 (area=1.056 km², *Source*: Google Earth) and June 2012 (area=1.2135 km², *Source*: Global Land Ice Measurements from Space, www.glims.org and ASTER/JPL/NASA).

Sakai et al. (2003) compared the bathymetric surveys over a 10-year interval (1992 and 2002) at Imja Lake to reveal the rate of lake volume increase. This study adds another decade of data to the analysis of lake changes (Table 3). The volume of the lake was 78% larger in 2012 than in 2002, expanding at a rate of 2.83 million m³/yr. The areal expansion rate decreased to 0.020 km²/yr and the average depth increased by 1.8 m/yr in the decade 2002 to 2012 and it is currently increasing at 5.8 m/yr.

Table 3. Comparison of Imja Lake Characteristics Over Two Decades

Decade	Volume Increase (%)	Volume Expansion Rate (million m ³ /yr)	Area Expansion Rate (km ² /yr)	Average Depth Change Rate (m/yr)
1992-2002	30	0.78	0.026	-0.54
2002-2012	78	2.83	0.020	1.75

The volume of water in the lake has an impact on a potential GLOF and the risk to downstream communities if the terminal moraine of the lake becomes unstable. The increase in lake area since the previous surveys is due to the rapid glacier recession in the last few years. This has important ramifications for the estimation of a potential GLOF since there is an increased volume of water available for the flood. It also has an impact on the design of any glacier lake management system, e.g., a drainage channel at the outlet as has been suggested (UNDP 2012), since the flow needed to reduce the lake level will be increased. If we take the lake elevation as 5010 m (a consistently measured value based on several GPS devices during the recent survey) and the elevation of the valley at the base of the lake outlet as 4980 m, then there is a 30 m elevation difference. The difference in lake area between 2009 and 2012 is 0.20 km² (1.21 – 1.01 km²), so the additional volume of water that can be drained from the lake in a GLOF is 6 million m³. The maximum possible GLOF increases from 30.3 million m³ to 36.3 million m³. Sakai et al. (2003) calculated a potential GLOF of 21 million m³ based on 2002 data; whereas by 2012 this has increased to 36.3 million m³, a 73% increase.

Figure 13 shows a comparison of 2012 bathymetric survey results with those of the 1992 (Yamada & Sharma 1993) and 2002 (Sakai et al. 2003) surveys. The up-glacier expansion of the lake is evident in the figure as well as the rapid retreat of the glacier ice cliff and the major subaqueous melting that has taken place. Sakai et al. (2005) found that the bathymetric

expansion of Imja Lake was mainly the result of glacier retreat. They assumed that the water level in 1992 was equal to that in 2002, and their cross sections revealed no great difference from the outlet to the glacier cliff between 1992 and 2002, as shown in Figure 13). The shallower depth recorded in 2002 may be a result of abundant sediment produced at the base of the glacier and carried away by glacier melt water and deposited in the lake basin or possible locational error (Sakai et al. 2003). This is also the likely reason for the discrepancies between the curves in Figure 13 up to 1750 m. Beyond that point, the lake has deepened significantly due to subaqueous melting and calving.

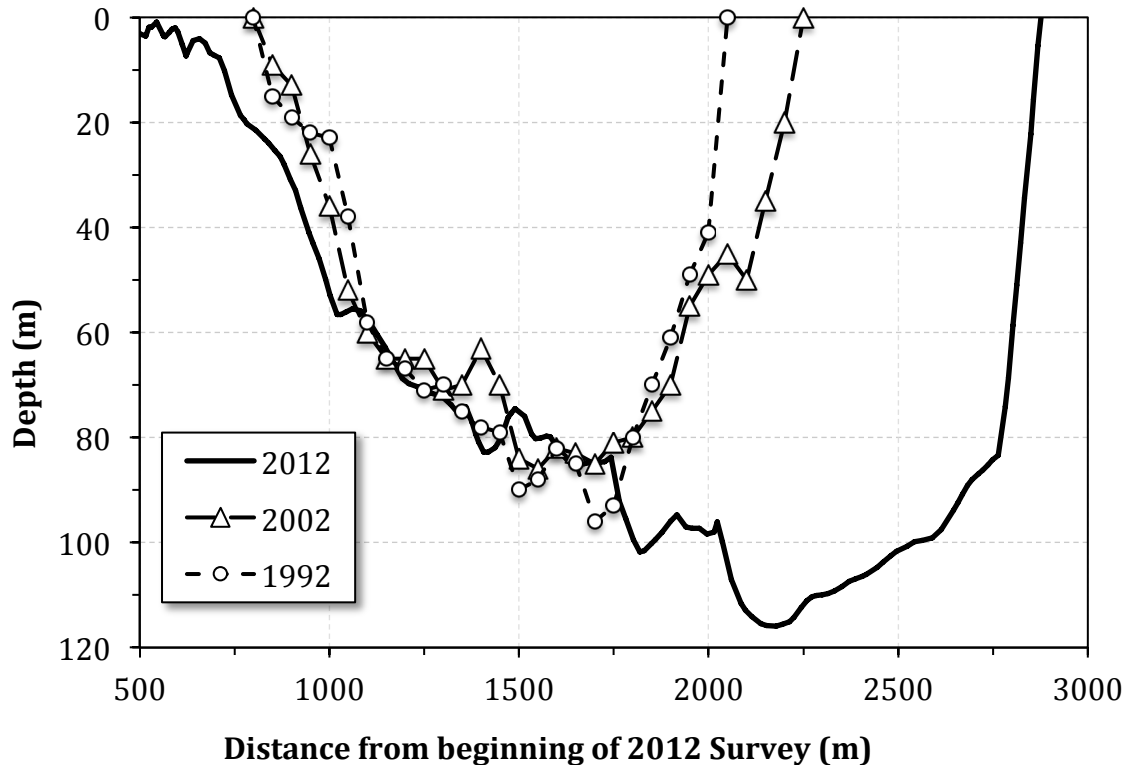


Figure 13. Comparison of 2012 bathymetric survey results with those of the 1992 (Yamada & Sharma 1993) and 2002 (Sakai et al. 2003) surveys.

4 DISCUSSION

The results of the bathymetric survey reported here illustrate the dynamic nature of Imja Lake and how increased temperatures and other environmental factors have been influencing its evolution over the past decades and the past few years in particular. There are several factors that need to be considered regarding the retreat of Imja Glacier and the expansion rate of Imja Lake. A number of these factors are discussed below, including (1) average growth rate; (2) terminal moraine shrinkage; (3) subaerial (above the waterline) cliff calving; and (4) subaqueous calving.

Figure 14 illustrates a conceptual model cross-section of Imja Lake based on this bathymetric survey and ground penetrating radar (GPR) surveys described in Somos et al. (2012). The thickness of the ice near the face of the Imja Glacier is about 220 m, about 73 m below the

bottom of Imja Lake. It is clear that the ice beneath the bottom of the lake continues to melt, but the thickness of that ice is unknown. The previous GPR surveys have indicated the presence of extensive ice up to 60 m thick in some areas of the outlet complex and terminal moraine. The transition from relatively clean glacier ice to the ice and rock mixture of the outlet complex is unknown but may be significant toward the up-glacier end of the lake since the bottom topography near the outlet end of the lake has not changed much over the past decade.

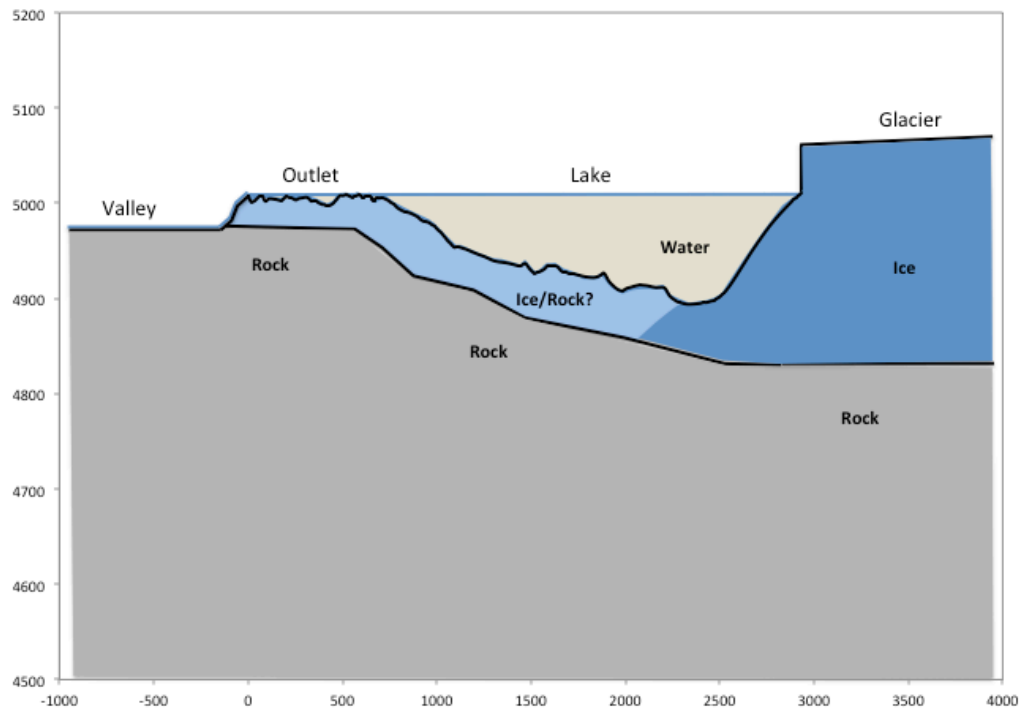


Figure 14. Conceptual model cross-section of Imja Lake based on bathymetric survey and ground penetrating radar surveys. (5x vertical exaggeration).

Average growth rate: ICIMOD (2011) shows values for the average growth rate of Imja Lake. For the period 1962 – 2001 the rate is given as 42 m/year and for the period of 2001 – 2006 as 74 m/year. These values are based on the differences in the length of the lake, but the method of measuring the length of the lake is not specified. In this research, the area of the lake in 2010 has been calculated from GIS to be 1.05 km² and in 2012 to be 1.21 km². The average width of the lake has been calculated to be 601 m. Based on these figures, the difference in the area over this two-year period is 0.162 km² and the average growth rate over the period is 135 m/year, significantly in excess of previously reported rates. Benn et al. (2012) note that debris cover on glaciers, especially thin cover, and may cause a strongly non-linear chain of cause and effect of mass loss and lake formation. This may be what has been observed at Imja Lake over the past 2 years. Figure 15 shows the Imja Glacier near its terminus, the thin covering of debris and the clean ice structure beneath.



Figure 15. Imja Glacier showing the thin covering of debris and the clean ice structure beneath.
(Photo: Daene McKinney)

Terminal Moraine Shrinkage: The western shoreline of Imja Lake is changing rapidly. Figure 16 shows the rapidly disappearing shoreline at the western end of Imja Lake. The image in the left of the figure (February 2010) shows a major peninsula jutting into the lake from the south side of the lake. The right of the figure shows a photograph of the remains of the peninsula in May 2012, illustrating the rapid decomposition and narrowing of the terminal moraine complex.

Figure 17 shows an ice face below the top of the left lateral moraine of Imja Lake on the south side of Imja Lake in May 2012. The ice cliff indicates the presence of large amounts of ice remaining in the core of the moraine and extending into the terminal moraine complex (Somos et al. 2012). The moraine in this area is decomposing rapidly and causing a narrowing of the lateral and terminal moraine in this area. The narrowing of the moraine greatly increases flood risk (Benn et al. 2012); therefore, if this continues it could be major problem in the future.

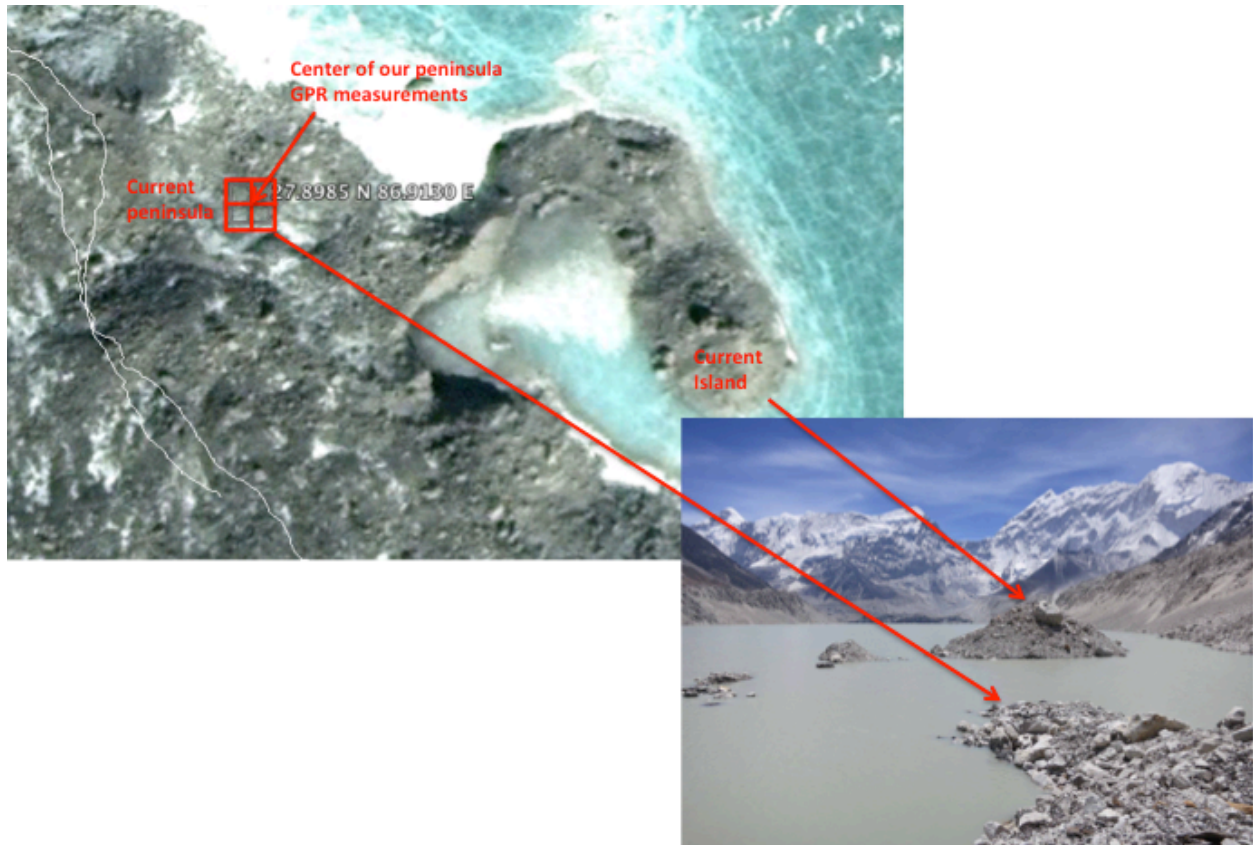


Figure 16. Rapidly disappearing shoreline at the western end of Imja Lake. Left: Google Earth Imagery from February 2, 2010. Right: Photo from May 2012 (*Photo: Daene McKinney*)



Figure 17. Ice face visible below the top of the left lateral moraine of Imja Lake. The 2 m person is shown in the photo for scale. (*Photo: Marcelo Somos-Valenzuela*)

Subaerial Cliff Calving: Calving is an important glacier ice-loss mechanism, and can result in larger volumes of ice lost from glaciers than would be possible through surface ablation alone (Boyce et al 2007, Van der Veen, 2002; Benn et al. 2007). Calving mainly affects glacier terminus geometry and retreat rate, and large glaciers calving into deep water tend to lose more mass through calving than ablation (Boyce et al 2007). Calving occurs in a cyclic pattern of melting at the waterline that creates an overhanging subaerial cliff that calves progressively larger ice lamellae by flaking and eventually full height slab calving (Robertson et al. 2012). Kirkbride and Warren (1997) describe four stages of ice cliff calving into glacier lakes and these are illustrated with the authors' observations of these stages at Imja Lake: (1) waterline melting and collapse of the roof of thermo-erosional notches at the cliff foot (Figure 18); (2) calving of ice flakes from the cliff face leading to a growing overhang from the waterline upwards, and crack propagation from the glacier surface (Figure 19); (3) large calving of slabs in response to the developing overhang (Figure 20); (4) subaqueous calving of a submerged ice foot (see Figure 21). The cyclic process of waterline notches growing upwards by flake calving inducing crevasse propagation and full-height slab calving restores the vertical profile to the waterline and forms a submerged ice foot, which experiences subaqueous calving (Kirkbride and Warren 1997).



Figure 18. Waterline melting and collapse of the roof of thermo-erosional notches at Imja Lake in September 2011 (*Photo: Daene McKinney*).



Figure 19. Calving of ice flakes from the cliff face at Imja Lake (*Photo: Daene McKinney*).



Figure 20. Calving of ice lamella at Imja Lake (left September 2011, right May 2012) showing forward bending causing surface crevasses to propagate downward (*Photo: Daene McKinney*).

Subaqueous Calving: According to Robertson et al (2012) subaqueous ice ramps appearing at the glacier end of glacier lakes tend to be sloped upwards at between 11° and 30° and exhibit subaqueous calving. The distance between the 110 m depth contour and the 20 m depth contour (Figure 11) on the glacier end of Imja Lake (90 m depth difference) is 453 m, giving a slope of 11° . Figure 6 in Sakai et al. (2005) shows that the slope of the bottom of the lake at the glacier end was 12° in both the 1992 and 2002 surveys. The rate of deepening of Imja Lake is far in excess of the rate that would be expected if the controlling process was the melting of underlying glacier ice into the lake. Subaqueous calving may explain the rapid deepening. The authors observed subaqueous calving at the glacier end of Imja Lake in September 2011 (Figure 21 and Byers 2011). The bergs, which most likely detached from a submerged, projecting ice foot or ramp, broke the lake surface at distances of up to 200 m from the ice cliff, from water about 75 m deep. This is similar to subaqueous calving events observed by Kirkbride & Warren (1997) for New Zealand lake-terminating glaciers.



Figure 21. Subaqueous calving event at Imja Lake in September 2011. Upper left – before the commencement of calving. Upper right – appearance of iceberg. Lower left – disintegration of iceberg. Lower right – end of calving event. (*Photos: Daniel A. Byers*)

CONCLUSIONS

Imja Lake is one of the most studied lakes in the Himalaya as well as one of the most rapidly evolving glacial lakes in Nepal. Many researchers have studied the lake and the potential of a GLOF from the lake. One of the important factors in assessing the GLOF risk is the volume that could be released in the flood and good bathymetric data is necessary for estimating that volume. This work has reported on the 2012 bathymetric survey of Imja Lake and the rate of expansion that has been observed in the lake over the last two decades, since 1992. The survey was somewhat hampered by the extensive iceberg coverage of the lake in September 2012, but a good estimate of the bottom bathymetry and the current volume was obtained. It is very clear, when compared to the previous surveys that the lake bottom has continued to deepen as the ice beneath the lake has melted. As reported in the results section, the average depth has increased by 62% since 2002 and continues to increase at a rate of 1.8 m/yr. The maximum depth has increased 28% since 2002 and is increasing at a rate of 5.8 m/yr. Perhaps more important in terms of GLOF risk is the continued rapid areal expansion of the lake, since it has expanded 41% since 2002 and is growing at a rate of 0.02 km²/yr. This expansion provides an additional 6 million m³ of water for a GLOF event increasing the maximum possible GLOF volume to 36.3 million m³ a 73% increase from what was calculated using 2002 data.

Imja Glacier seems to be experiencing a period of non-linear accelerated melting causing a more rapid than expected expansion of Imja Lake due to rapid calving retreat. Rapid calving retreat (Kirkbride, 1993) was observed by the authors at Imja Lake over field visits in 2011 and 2012, and has contributed to a 78% increase in the volume of Imja Lake from 2002 to 2012,

significantly greater than in previous decades (Somos et al 2012). Calving occurs in a cyclic pattern where waterline notches develop and grow upward by flake calving, which induce crevasse propagation and full-height slab calving that restores the vertical profile to the waterline and forms a submerged ice foot that undergoes subaqueous calving (Kirkbride & Warren 1997). This entire cyclic process was observed at Imja Lake in 2012 and it is a function of the lake characteristics, i.e., relatively constant water level, shallow thermocline, and large depth that promotes thermal notch development and full height slab calving. Further field work is necessary document the accelerated expansion using in situ observations of the calving processes and repeat bathymetric surveys as well as the development of calving models linking the formation of thermal notches to the local stresses in the ice cliff that result in fractures and cause full height slab calving events and the creation of ice feet that lead to subaqueous calving. The increased rate of retreat of the Imja Glacier is cause for concern as it rapidly increases the volume of the lake, which has an impact on GLOF hazard and risk to downstream communities if the terminal moraine of the lake becomes unstable. Furthermore, as the lake retreats up-glacier it becomes more susceptible to GLOF triggering events such as rockslides and avalanches that are more common on the steeper slopes (Figure 22). The effects of climate change further exacerbate the rapid lake expansion as the increasing melt water increases the retained lake volume. Furthermore, the increased mass loss in the mid-ablation zone leads to the development of perched lakes up-glacier that will continue to grow until englacial conduits form allowing them to drain into Imja Lake or until the rapid calving retreat of Imja Lake reaches the perched lakes.



Figure 22. Avalanche onto the Imja Glacier September 2012 (*Photo: Daniel A. Byers*)

Rapid expansion of Imja Lake combined with a weakening ice core present in the terminal moraine dam and the onset of seepage from the base of the dam is increasing the risk to downstream communities. In the last decade, the risk of a breach in the terminal moraine dam was classified as very low due to the low risk of surge waves generated by calving or avalanches, the moraine's large width relative to its height, and the low hydraulic gradient of the free-draining channel being unlikely to incise the moraine (Hambrey et al. 2008). However,

observations from field visits in 2011 and 2012 showed the western side of Imja Lake is rapidly transforming (Figures 16 and 17). Small peninsulas apparent in satellite imagery have melted, showing that the terminal moraine is vulnerable and likely undergoing a similar transformation of decomposition and narrowing. Ice cliffs are decomposing into the lake. Small ponds have also been developing throughout the terminal moraine complex. These small ponds are excellent sources of heat to the surrounding ice, which only further exacerbate the decomposition of the terminal moraine complex, yet their development and impact on the terminal moraine complex has not been analyzed. Somos et al. (2012) utilized Ground Penetrating Radar (GPR) throughout the terminal moraine to yield insight into the stability of the ice core beneath the terminal moraine. These results confirmed that there is a large ice core beneath the terminal moraine that is susceptible to melting; however, extensive electrical resistivity surveys are needed to better understand the terminal moraine complex. Further information is needed to assess the current risk and predict the decomposition of the terminal moraine complex in the future, especially as Imja Lake continues to expand rapidly. Furthermore, current risk reduction strategies being pursued through a UNDP Global Environment Facility proposal are to incise a concrete channel into the terminal moraine structure to lower the lake level by 3m. In order to assure that this is an effective risk mitigation strategy, it is imperative to have additional knowledge of the terminal moraine complex. An understanding of the location of ice throughout the entire moraine and the seepage through the moraine is required in order to develop mitigation strategies that will not negatively impact the structure of the terminal moraine.

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